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13. ABSTRACT (*Maximum 200 words*)

The report provides an overview of the infrastructure and capabilities established in the framework of the cooperative agreement. The capabilities include custom-configured instrumentation for optical characterization of display components and systems, as well as custom-designed equipment for fabrication and characterization of flexible flat panel display components, including organic light emitting diodes (OLEDs).

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1. SUMMARY

The objectives of the Cooperative Agreement were to:

- Establish infrastructure for characterization of display components and systems.
- Establish infrastructure for fabrication and testing of organic light emitting diode devices.
- Establish testing procedures based on display standards.
- Obtain data on commercial off-the-shelf (COTS) displays available on the US market in preparation for construction of an electronic database.

The program was launched with a kickoff meeting that took place at ARL in Adelphi, Maryland, on October 18, 2000. The meeting was hosted by David Chiu and David Morton of ARL. During the kickoff meeting, the key program personnel were introduced, the proposed tasks were discussed, and the program schedule, milestones and the initial program management plan were presented. A follow-on meeting took place on February 27 at the Systems Planning Corporation in Arlington, VA. The meeting was hosted by David Chiu and David Morton of ARL. In addition to MCNC staff, the participants included Henry Girolamo of Natick (U.S. Army Soldier Systems Center), Charles Bradford of Night Vision and Electronic Sensors Directorate (NVESD), Ron Enstrom and Michael Brill of National Display Laboratory (NDIL) at Sarnoff Laboratories, and Paul Boynton of NIST. The objective of the meeting was to brief representatives of the other DoD organizations and DoD contractors regarding capabilities that were being established at MCNC as a result of the cooperative agreement and review some of the work that was being done under government sponsorship at other organizations.

The initial performance period for the cooperative agreement was from 7/1/00 to 6/30/01. A no-cost extension was requested for the period of 7/1/01 to 6/30/02 to allow MCNC to finalize purchases of the fabrication and characterization equipment, most of which was custom designed and had long delivery times. The review of the program took place on September 18, 2001 at MCNC.

The capabilities established in the framework of this Cooperative Agreement are being used in a follow-on program titled "Display Development and Characterization Laboratory" (Contract No. DAAD17-01-C-0085). Reports on progress in the follow-on program are available separately.

2. INFRASTRUCTURE FOR CHARACTERIZATION OF DISPLAY SYSTEMS

In preparation for the task of specifying the characterization equipment, MCNC staff reviewed commercially available instrumentation using the criteria of high quality, full wavelength range, wide dynamic range, sensitivity and stable calibration.

Tables I to VII present results of a survey of commercially available photonic instrumentation. In Table I, we survey photometers, radiometers and colorimeters. In Tables II, III and IV we survey serial-recording spectroradiometers, linear CCD-Array spectroradiometers and CCD cameras, respectively. Tables V and VI present results of a survey of automatic test systems. Table VII presents information on goniometers, and Table VIII presents a survey of available light calibration sources.

Photometers, Radiometers & Colorimeters					*No gratings, so typically no polarization error*
Supplier	Model	Wavelength Range	Sensitivity Range	Min. Meas. Spot	Note
Gamma Scientific	DR-1600 (D-1500-2B)	200 nm - 1100 nm (Si)	E-02 to E+04 Lux		
Gamma Scientific	DR-1600 (D-100-2S)	800 nm- 1800 nm (InGaAs)	E-02 to E+04 Lux		
Gamma Scientific	DR-2000 (D-1500-2B)	200 nm - 1100 nm (Si)	E-03 to E+04 Lux		RS-232 interface; computer controlled
Gamma Scientific	DR-2000 (D-100-2I)	800 nm- 1800 nm (InGaAs)	E-03 to E+04 Lux		RS-232 interface; computer controlled
Gamma Scientific	GS-1400 ACR (ANVIS Compatibility)	450nm - 930nm		1.6 mm (contact measurement)	Measures ANVIS radiance by MIL-L-85762
Hoffman Engineering	Topcon BM-7				RS-232 or GPIB interface
International Light	IL1700 Research Radiometer	Depends on detector	E-13 to E-3 Amp		
Optronic Laboratories	OL230C Programmable Radiometer/Photometer	Depends on detector	E-15 amp with preamp in detector head		
Photon Technology International	D-104B Microscope photometer		Photon-counting PMT	1 μm (depends on microscope objective)	
Photo Research	PR-880	Photopic	Min E-5 cd/m^2	12 μm	
Photo Research	PR-1980A	360nm - 830nm (unfiltered)	E-7 to E+8 cd/m^2 (depending on aperture) PMT	2 μm with 7mm working distance; 50x objective	

Table I. Survey of commercially available photometers, radiometers and colorimeters (as of 9/30/00).

Serial-Recording Spectrometers							
Supplier	Model	Wavelength Range	Spectrum sampling interval	Wavelength Resolution	Minimum measuring spot size	Sensitivity	Note
Gamma Scientific	C-11ASR	370nm - 1010nm	0.1nm (cooled PMT)	0.2nm			Aperture perpendicular to axis; no polarization error
Oriel	Cornerstone 260 Motorized Monochromator	Wide range - holds three gratings		0.15nm	Depends on input optics	Depends on detector (has 2 detector ports)	Motorized & interfaced; LabView VIs
Instrument Systems	DTS320-201 night vision tester	380nm - 930nm		0.5nm to 10nm	150 μm	0.01 cd/m^2	
Instrument Systems	Spectra 320	190nm - 5000nm	0.05nm	0.2nm to 10nm			
McPherson	Model 2035	185nm - 78μm		0.03nm			
International Light	IL2000 SpectroCube	250nm - 1100nm		0.2 nm			Internal self-calibrating; battery & modem operation
Optronic Labs	OL Series 750 Automated Spectroradiometer	200nm - 30μm					
Analytical Spectral Devices	FieldSpec FR	350nm - 2500nm	1nm	10nm			Field portable

Table II. Survey of commercially available serial-recording spectrometers (as of 9/30/00).

Linear CCD-Array Spectroradiometers							
Supplier	Model	Wavelength Range	Spectrum sampling interval	Wavelength Resolution	Minimum measuring spot size	Sensitivity	Note
Gamma Scientific	GS-1280 RadOMAcam	380nm - 810nm	0.5 nm/pixel (1024 pixels)	5nm (independent of aperture size)	84 μm		Free of polarization error
Melchers		300nm - 800nm		5nm			
Minolta	CS-1000 Spectroradiometer	380nm - 780nm	0.9nm	5nm	1.15mm	30 cd/m^2 (with macro lens)	Less than 5% polarization error
Instrument Systems	DTS140-201 FPD & CRT tester	380nm - 1100nm	(CCD)	2nm		0.5 cd/m^2	
Ocean Optics	S2000 High-sensitivity fiber optic spectrometer	200nm - 1100 nm	(2048 element CCD)	0.3nm - 10nm			Low cost
Photo Research	PR-705	380nm - 780nm		2.5nm - 20nm	0.12mm	0.003 cd/m^2 for large aperture (cooled CCD)	Less than 5% polarization error; diagonal aperture
Photo Research	PR-650	380nm -780nm	3.5nm (128 element CCD)	8nm	0.51mm	5 cd/m^2	Diagonal aperture; edges defocused; 1% polariz. error

Table III. Survey of commercially available linear CCD-array spectroradiometers (as of 9/30/00).

CCD Cameras						
Supplier	Model	Array Size	Pixel Size	Frame Grabber	Bit Depth	Wavelength Range
Roper	MegaPlus 1.0	1008 x 1018	9μm	NI PCI-1424	10 bits	Visible
Roper	MegaPlus 4.0	2048 x 2048	7.4μm	NI PCI-1424	12 bits	Visible
FLIR Systems	ThermaCAM SC2000	320 x 240		PCMCIA	14 bits	7.5μm - 13μm

Table IV. Survey of commercially available industrial CCD cameras (as of 9/30/00).

Automated Display Test Systems					
	Goniometer	Non-Tilting Configuration	Goniometer	Goniometer-Theodolite	Conoscope System
	Westar FPM-520	Westar MicroDisplay Test System	PhotoResearch PR-9000	Spectron Engineering DASH	Eldim EZContrast AX160D
Stage x-max	48 inches	12 inches	30.5 cm	option	400mm (motor)
Stage y-max	30 inches	4 inches	1.07 m	option	250mm (motor)
Stage z-max	48 inches			option	80mm (motor)
Stage delta x(min); delta y(min)		0.5 μm		option	0.01mm
Rotation phi(max); theta(max)	+/- 90 degrees	No tilt	+/- 90 degrees	option	+/- 80 degrees; 360 degrees
Rotation delta phi(min); delta theta(min)		No tilt	0 degrees 10' accuracy	option	0.1 degrees
Stage temperature control	heating/cooling chamber as option	Peltier heating/ cooling stage as option	none	compatible with heating/ cooling chamber	-40C to +80 C
Spectrometer wavelength range	any spectrometer	400nm - 700 nm	380nm - 1068nm PR-715	Chromaticity only; spectrometer as option	Chromaticity only

Spectrometer wavelength resolution	any spectrometer	1.33 nm	≥2.5nm	Chromaticity only; spectrometer as option	Chromaticity only
Spectrometer measuring spot size	depends on working distance	depends on objective lens	depends on working distance	depends on working distance	2 mm diameter max
Photometer measuring spot size	depends on working distance	depends on objective lens	depends on working distance	depends on working distance	2 mm diameter max
Stage load capacity	80 lbs		20 lbs	Unlimited (display does not move)	22 inch diagonal
CCD array size		1300 x 1030			
Video drivers	Selection of drivers			Selection of drivers	Programm-able drivers

Table V. Survey of commercially available automated display test systems (as of 9/30/00).

Camera-Based Automatic Test Systems					
Supplier	Model	Array Size	Bit Depth	Wavelength Range	Note
Integral Vision	LCI-Profes-sional	4096 x 4096			Tests bad pixels; background uniformity
Radiant Imaging Inc	ProMetric Color	1024 x 1024 cooled CCD	16 bits	Luminance & Chromaticity	Fully computerized
Photo Research	PR-900 Video Photo-meter	512 x 512 cooled CCD	8 bit	Luminance & Chromaticity	

Table VI. Survey of commercially available camera-based automatic test systems (as of 9/30/00).

Goniometers		
Supplier	Model	Note
Newport	BGM	With motor drive
Radiant Imaging		
Instrument Systems	5-axis positioner	Software moves the head to compensate for rotation

Table VII. Survey of commercially available goniometer systems (as of 9/30/00).

Light sources for calibration			
Supplier	Model	Wavelength Range	Note
Gamma Scientific	NIST traceable calibration source RS-12	Tungsten source	NVIS filter to simulate green display with near IR
Gamma Scientific	RS-5 Digital light source system	LED sources; blue to near IR	Programmable calibration source
Gamma Scientific	GS-5100 Diffuse Reflectance/ Transmittance	200nm - 1100nm; tungsten & deuterium	
Gamma Scientific	5000-16C 1000-watt FEL lamp source	250 nm - 2.5 μm; tungsten	NIST selected FEL for calibration
Hoffman Engineering	LS-65-8D		Internally monitored luminance standard
Instrument Systems	ISP 40 Integrating sphere		44mm diam Teflon sphere
Instrument Systems	ISP 150 Integrating sphere	300nm - 2600nm	150mm sphere
International Light	INS250 Integrating sphere	225nm to 1400nm (450nm - 900nm @ 97% reflectance)	250mm sphere internally baffled
Optronik GmbH	Idn 10-3 luminance standard	2856 K tungsten	300mm sphere & light source
Oriel Instruments	70445 high efficiency mono-chromate sphere	250nm - 2100nm	2-inch thermoplastic sphere
Oriel Instruments	70451 general purpose sphere		6-inch sphere for general use
Oriel Instruments	70481 uniform light source sphere		8-inch; best uniformity and worst throughput

Table VIII. Survey of light sources for calibration (as of 9/30/00).

On the basis of the survey of the available brand names and models, discussion with vendors, visits to vendor facilities and reference checking, we have specified and purchased the optical test equipment listed in Table IX and described in detail below. The majority of the equipment is custom-configured.

Westar FPM-500 Goniometer System

The FPM-500 System, combined with detectors, is capable of performing optical measurements as a function of the position of the emitting spot. Measured properties include luminance and chromaticity, emission uniformity and viewing angle uniformity. Automated test sequences with data reporting are also available. The FPM-500 system includes a five-axis motion base, dampened optical table, system controller PC, and system interface cabling. The motion base consists of a 3-axis instrument positioner and a 2-axis device under test (DUT) goniometer. This allows the instrument and DUT to be positioned in such a way that any point of the DUT can be measured at various viewing angles while maintaining consistent instrument working distance and location.

The system includes Westar ViewPoint™ software. The ViewPoint™ applications, known as the Manual Control Interface (MCI) and the Automated Test Sequencer (ATS), come pre-installed on the system controller PC along with the Windows-NT operating system, National Instruments LabWindows CVI/Test Executive, and Microsoft Excel. The ViewPoint™ MCI allows one to directly control the FPM-500 motion base, optical instruments, and DUT. The ATS is useful for writing and performing automatic test sequences. By using the standard test primitives, we developed our own tests to position the DUT and optical instruments, and making measurements. Resulting data are automatically logged to a Microsoft Excel spreadsheet report.

In order to be able to test miniature display prototypes, we have purchased a Miniature Display Goniometer. This upgrade changes the goniometer design to a polar arrangement allowing close examination of the smaller spot sizes. The upgrade includes modifications to the system software to accommodate the polar goniometer geometry.

Photo-Research PR-880 Filter Photometer

This instrument can either be used independently, or with the FPM-500 system. The PR-880 is the only fully automated filter photometer available today. It allows measurements of luminance, illuminance, luminous intensity, and tristimulus color coordinates of optical devices. We have purchased two lenses for the instrument: one, MS-55, for the distance range of 44 mm to ∞, and one, MS-5X, for the distance of 28 mm; the latter to enable measurements of miniature (sub-inch) display prototypes. PR-880 incorporates five automated apertures: 3°, 1°, 1/2°, 1/4°, and 1/8°. The ability to change apertures allows one to vary the field coverage (from 2.89 mm for the 3° aperture to 120 μm for the 1/8° aperture in the case of the MS-55 lens, and from 380 μm for the 3° aperture to 20 μm for the 1/8° aperture in the case of the MS-5X lens). Changing the aperture changes the sensitivity of the measurement (from 3×10^{-5} cd/m^2 for the 3° aperture to 3×10^{-3} cd/m^2 for the 1/8° aperture in the case of the MS-55 lens, and from 3×10^{-4} cd/m^2 for the 3° aperture to 3×10^{-2} cd/m^2 for the 1/8° aperture in the case of the MS-5X lens). PR-880 can be controlled from any computer over the built-in RS-232 interface.

Optical Test Equipment

	Vendor	Status	Notes
Detector Systems			
PR-880 Filter Photometer	PhotoResearch	operational	Includes accessories
PR-705 SpectraScan Spectroradiometer	PhotoResearch	operational	Wavelength range 380 nm - 780 nm; includes accessories
Prometric Color Digital Camera	Radiant Imaging	operational	Digital CCD Camera 2184x1472 Class 1 CCD chip
Temporal Response Detector+DAQ Card	Westar	operational	Allows for measurement of response time
2000 Series Fiber Optic Spectrometer	Ocean Optics	operational	350-1000 nm, calibration source included
CS-100 Chroma Meter	Minolta	operational	
Goniometer Systems			
FPM-500	Westar	operational	5-axis motion base; computer control
Conoscope Systems			
Eldim Conoscope	Eldim	operational	Aperture angle of up to ±60°
Pattern Generators			
Team Systems Video Generator VG-827	Westar	operational	
Programmable Generator	Westar	operational	
Miscellaneous Test			
Power Consumption Test Set	Westar	operational	Includes programmable power supplies
Ambient Contrast Ratio Apparatus	Westar	operational	
Sunlight Contrast Ratio Apparatus	Westar	operational	
Optical Microscopes and Projectors			
Olympus BX-51 Material Microscope	OPELCO	operational	
Digital camera for Olympus BX-51	OPELCO	operational	
Projectors (2)	NEC	operational	For display tiling project

Table IX. The list and status of the optical test instrumentation.

Photo-Research PR-705 SpectraScan® System

This instrument can either be used independently, or with the FPM-500 system. PR-705 is a self-scanning spectroradiometer. A single wide-band detector (photomultiplier tube) measures and records the amount of light at each wavelength. Since the scan is on a wavelength-by-wavelength basis, the computing ability of the system allows the data to be easily converted into many measurement units and displayed in several formats. Integration of the device light output over selected wavelength or time intervals with appropriate computations can yield luminance, radiance, tristimulus color coordinates, and color temperature. The wavelength range of PR-705 is between 380 nm and 780 nm, with the spectral accuracy of $\pm$ 2 nm. The spectral bandwidth is $\geq$2.5 nm (the bandwidth is dependent on the aperture). As in the case of PR-880, PR-705 will be equipped with two interchangeable lenses: MS-55 and MS-5X. To increase the flexibility of the instrument, we have specified six apertures to be included on the automated aperture wheel: circular 2°, 1°, 1/2°, 1/4°, and 1/8° apertures, and a 1/2°× 1.5° slit aperture. The sensitivity of PR-705 varies from 3×10^{-3} cd/m^2 for the 2° aperture to 3×10^{-3} cd/m^2 for the 1/8° aperture in the case of the MS-55 lens, and from 3×10^{-4} cd/m^2 for the 2° aperture to 1 cd/m^2 for the 1/8° aperture in the case of the MS-5X lens. PR-705 comes equipped with the SpectraWin™ Windows-based software that provides a control of the instrument functions, as well as the display and calculation platform.

Prometric Color Digital Camera

This is a digital 14-bit cooled CCD camera with the resolution of 2184×1472. The camera is purchased with the ProMetric™ Software for computer interface. The camera allows a rapid measurement of 2-D distribution of luminance, illuminance, luminous intensity, chromacity coordinates and correlated color temperature. Its field of view is 2 degrees to 72 degrees. In contrast to the goniometer-based systems, where the measurements are obtained point-by-point, the camera captures the image of the targeted area instantaneously, and the photometric data are available for every pixel. Westar developed a custom software for integration of the Prometric Camera onto the FPM-500 platform that allowed us to add this photometric calibrated camera to the list of compatible detectors.

Eldim Conoscope System

Conoscope is an all-optical system that quickly measures viewing performance. The key component of the system is a high-performance Fourier transform lens. It covers an aperture angle of up to ±60°, so that it can simultaneously collect and analyze a 120° cone of light from a point on the display. All contained light directions transform to points in the rear focal plane, producing the "conoscopic figure," which is a feature of the spatial emission characteristics. The conoscope records luminance and chromaticity vs. viewing direction. A high-sensitivity photometric/colorimetric CCD array analyzes the conoscopic figure.

Auxiliary Instrumentation

- Temporal Response Detector (TDR-100A)
- Ocean Optics 2000 Series Fiber Optic Spectrometer
- User self-calibration software for PR-880 and PR-705
- He wavelength calibrator
- Automated luminance/color temperature/radiance standard with 6" integrating sphere
- Power consumption and L-P ratio test set (contains HP6600 Programmable DC power supply)
- Ambient contrast ratio apparatus (includes a 20" integrating hemisphere, mounting hardware, illumination light sources, controllable power supply and a reflectance standard)
- Sunlight contrast ratio lighting apparatus
- Team Systems VG-827 pattern generator (provides analog and digital RGB and synchronization signals)

3. Infrastructure For Fabrication And Testing Of Organic Light Emitting Diodes And Other Flexible Display Components

In support of the cooperative agreement, full capabilities for fabrication and evaluation of OLED and PLED devices were established. Table X lists the device fabrication and characterization equipment and includes information on the equipment status.

3.1. Infrastructure for fabrication of devices

For substrate preparation for both types of devices, a Jelight 144AX UV ozone cleaner was purchased for pretreatment of ITO-coated glass substrates. In addition, a fume hood and heated ultrasonic cleaner was installed in the lab with both OLED and PLED process systems for rapid transfer of clean substrates without leaving the cleanroom environment.

3.1.1. Infrastructure for small molecule-based OLEDs

The primary infrastructure for fabrication of OLED devices based on organic small molecules consists of a multi-chamber thin film deposition system custom-designed by MCNC and built by Angstrom Engineering, Inc. Figure 1 shows a schematic of the deposition system. Significant features of the system are described here. The two cryo-pumped deposition chambers are connected by a turbo-pumped load lock chamber, such that devices may be transferred between the chambers under vacuum. Both chambers achieve base pressure of 1×10^{-8} Torr or lower. Each chamber has a residual gas analyzer from Stanford Research Systems.

Substrate holders allow samples up to 6" in diameter, including specially designed holders for four (4) 50mm x 50mm glass substrates. One shadow mask can be stored in

Device Development Equipment

	Vendor	Status	Notes
Materials Analysis Systems			
UV-VIS-NIR spectrophotometer	Perkin-Elmer	operational	Transmission & reflectance of passive elements
PL spectrometer	Photon Technol.	operational	PL emission spectra
UPS source for XPS	Perkin-Elmer	installed	To measure work function of materials
Field emission SEM	Hitachi	operational	Low voltage images of organic materials
Deposition Equipment & Accessories			
Thermal multi-source evaporator	Angstrom Eng.	operational	For deposition of organic materials and metal electrodes
Glove box	Terra Universal	operational	Stainless steel+automatic purge
Environmental Testing			
Environmental Chamber	Assoc. Environm.	operational	Temperature and humidity
Miscellaneous Test			
Flexing Apparatus	Instor	operational	
Electronics			
DC source-meter	Keithley	operational	
Semiconductor Par. Analyzer	Agilent Technol.	operational	
Miscellaneous			
OSA	Agilent Technol.	operational	Resolution of 0.1 nm
Polymer deposition	Headway	operational	Spinner
UV ozone cleaner	Jelight Company	operational	Substrate preparation
Microscope for use w/ eucentric stage	OPELCO	operational	

Table X. The list and status of the device development equipment.

each chamber, and additional masks may be loaded via the load lock. Masks can be attached under vacuum and rotate with the substrates during deposition.

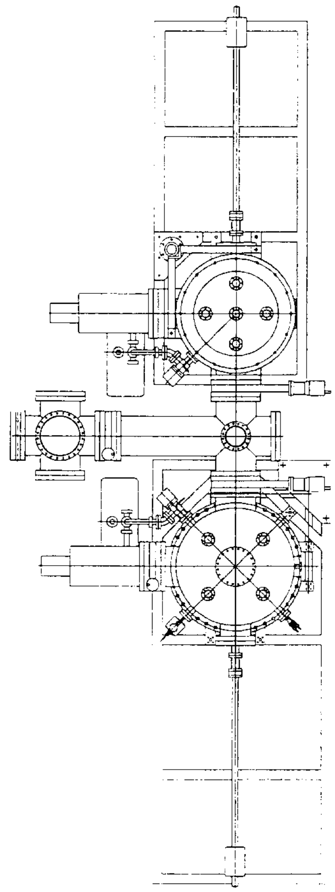

Fig. 1. Diagram of the OLED deposition system.

The organics system includes six thermal sources for evaporation of organic materials and two 4V/250A power supplies. Any two sources may be operated simultaneously to facilitate doped layers. Deposition is monitored via quartz crystal microbalances, and controlled using software from Sigma, Inc. which allows automated deposition of multilayer and doped films. Film uniformity is demonstrated to be better than +/- 2.5% (max-min).

The metal deposition chamber provides thermal evaporation from three sources with two 4V/500A power supplies, such that co-evaporation from two sources is possible. E-beam evaporation is provided by a Telemark 231-04 four pocket/4cc source, powered by a Telemark TT-3 3kW power supply. Co-evaporation using both e-beam and thermal sources is possible. RF magnetron sputtering is provided by a US Guns 3" Mighty Mak sputter source with and Advanced Energy 600W RF power supply. This power supply also provides power to the substrate for pre-sputtering of the substrate holder in the load lock. During evaporation the sputter source retracts to provide line-of-sight deposition from the evaporation sources. Sigma Inc. software is used to automate deposition of multilayer and doped films. The multi-chamber design with interchangeable masks allows fabrication of multilayer organic/inorganic structures without breaking vacuum.

3.1.2. Infrastructure for Polymer-based OLEDs

For fabrication of PLEDs, a stainless steel, nitrogen-purged glove box was purchased from Terra Universal. The glove box has a vacuum antechamber for sample transfer, a vacuum oven, and an automated purge system for minimization of moisture in the glove box atmosphere. A PWM32-PS-CB15 spin coater was installed inside the glove box to allow spin coating of polymer thin films under inert ambient conditions. For PLEDs, the polymer-coated devices are transferred to the OLED deposition system for metallization. In addition, the glove box is used for post-fabrication encapsulation of both OLED and PLED devices.

3.2. Infrastructure for testing of OLED devices

3.2.1. Optical and electrical testing

Routine optical and electrical characterization of OLED and PLED device performance includes measurement of current, brightness, and efficiency as a function of voltage. For these measurements, a Keithley 2400 SourceMeter is used as the power supply. This source/measure unit acts either as a current supply or a voltage supply, as well as either a current meter or voltage meter. Calibrated brightness as well as spectral measurements are provided by a PhotoResearch PR-705 spectroradiometer. These two units are controlled by a custom LabView program to provide automated I-V, B-V, and η-V measurements.

Degradation measurements are performed using a Keithley 2400 SourceMeter to provide a constant current source and voltage meter, along with an amplified photodiode to provide relative intensity values. These are controlled by a custom LabView program to provide relative brightness and efficiency measurements as a function of time.

3.2.2. Optical and chemical characterization of organic films and devices

Photoluminescence and photoluminescence efficiency are used to measure optical transition energies for luminescent materials. These techniques also provide a measure of intrinsic material efficiency and quality. For these measurements a QuantaMaster QM-2000-4SE photoluminescence system was purchased from Photon Technology International, Inc. This system includes a 75W Xe arc lamp source, a double grating excitation monochromator, a purgeable sample chamber with sample holders for cuvettes, powders, as well as a goniometer stage for thin films, a single grating emission monochromator, and a photomultiplier tube with extended NIR sensitivity which provides either analog or photon counting detection. The wavelength range of the system is 185-900 nm with 0.5 nm resolution, +/- 1 nm accuracy, and 6000:1 signal-to-noise ratio.

UV-Vis-NIR spectroscopy is used to provide general characterization of optical properties of materials. This can be particularly useful for measurement of absorption spectra of luminescent materials, as well as potential materials for transparent cathodes or passivation layers. For these measurements a Lambda 900 UV-Vis-NIR spectrometer was purchased from Perkim Elmer. This system includes fixturing for both transmission and reflection measurements, as well as fiber optic coupling fixtures for external measurements. The Lambda 900 system uses dual light sources, a dual two-grating monochromator, and both a photomultiplier tube and a PbS detector. These provide a wavelength range from 175 – 3300 nm, <0.05nm resolution, and +/-0.08 nm accuracy.

A J.A. Woollam M2000 spectroscopic ellipsometer was purchased to provide measurements of film thickness and dispersion curves for optical thin films. This instrument provides spectral dispersion data from 370 to 1700nm, has a 200mm automated stage for mapping, and has focusing optics for a <50 μm beam size.

3.2.2. Environmental testing

The environmental chamber is a *Model BHD-203* from *Associated Environmental Systems,* for low temperature/high temperature and humidity testing. The test chamber contains three cubic feet of working space and is designed to generate and control low and high temperature environments in the range of -65°C to +177°C (-85°F to +350°F). The controllable humidity range is 20% to 98% relative humidity. The test chamber comes equipped with a high/low temperature failsafe to prevent the temperature from exceeding a preset limit.

4. Establishing testing procedures based on display standards

We have established capabilities for a series of tests according to displays standards. These measurements are performed on the FPM-500 platform designed by Westar to control positioning of photometric detectors and of a flat panel DUT, and to record measured quantities. The Westar software contains an automated test sequencer (ATS) that enables to input commands for repetitive executions.

Below we list the capabilities for a suite of optical measurements of flat panel display devices. These capabilities follow the VESA and MIL standards. Our instrumental set-up is fully compatible with the suite of measurements, and many of them can be performed automatically.

- Luminance and color at full screen center (white and black), contrast ratio, and color gamut of full screen (red/green/blue) (VESA 302-1,-2,-3,-4)
- Full screen gray scale (gamma calculation, VESA 302-5)
- Checkerboard pattern luminance & contrast (VESA 304-9)
- Response time (by means of a high speed Temporal Response Detector, Westar TRD-100A , VESA 305-1)
- Five-point sampled uniformity of white and black, contrast ratio and color temperature (VESA 306-1,-2,-3,-6)
- Viewing angle test (VESA 307-1)
- Ambient contrast measurements with a 20" diameter hemisphere as illumination source (VESA 308-1,-2)

- Sunlight contrast measurement with sunlight simulator light sources (MIL-85762).
- Power consumption and luminous efficiency (VESA 401-1,-2).

Test measurements were performed using the PhotoResearch PR-880 photometer as a detector (except for the response time detection). For the purpose of the qualification of the instrumentation and demonstration of its capabilities, we purchased two commercially available low cost flat panel displays: a 14" diagonal flat panel monitor (KDS, model Radius), and a ¾" diagonal microdisplay, obtained from a disassembled personal display device (I-O Display System, model i-glasses). Results of selected measurements for these test displays are presented below.

We designed fixtures to attach the test displays to the goniometer sample holder. Testing of the displays requires the ability of producing display patterns such as full screen white, black, color gamut, checkboard and others. Measurements need to be performed with the detector pointing to a specific region on the pattern (e.g. white and black squares of a checkerboard). This means that the display drivers need to be coordinated with the detector position. In the Westar FPM-500, the DUT display patterns are provided by a display tuning device (DTS) connected to a second computer. With the ATS software control and the RS232 connection between the two computers, the system DUT pattern generation is fully integrated with the 5-axis motion and data acquisition. In our tests, displays were connected to the DTS through a standard VGA connector; the system allows for several other connection formats.

It was no surprise that the KDS display and the microdisplay had widely different performance. For example, the contrast ratio (white/black) with no ambient light was C_R=96 for the 14" computer monitor (a good value is over 200) while the microdisplay had a poor C_R=2.6. Viewing angle measurements of the microdisplay showed a poor performance (as expected), with the luminance decrease up to 50% for a 10 degrees viewing angle and a strong asymmetry between left and right turns.

Experimenting with DUTs showed that the automated test sequencer (ATS) is particularly valuable in the 5-point uniformity measurement. The test consists in measuring luminance of 5 patterns (white, black and RBG) in 5 different points of the screen. The operator aligns the detector at the geometrical center of the screen and inputs the display dimensions. The software calculates the location of the four points at the four angles of the screen and moves the detector accordingly, and for each detector position the DUT is automatically driven to display the 5 patterns. The total time required for this test is approximately 10 minutes, during which the operator does not need to be present. In this way, for example, we measured the KDS monitor uniformity as 3.5% on white pattern and 11% on black full screen pattern. In an analogous way the gamma measurement of a display requires changing 15 grayscale levels and performing a photometer measurement for each of them: the ATS performs the 15 measurements automatically and calculates the gamma parameter through a fitting procedure.

The suite of detectors compatible with the FPM500 system includes a time response detector, which is a photomultiplier with a pinhole providing a 1/8° aperture. The time response test is a measurement of the electro-optical response function resulting from the pixel activation/deactivation. The display tuning module drives the display on and off at a chosen time interval and the photomultiplier voltage response is acquired via an analog/digital card; the time required for the voltage to rise between 10% and 90% of its maximum value is defined as the rise time. We measured typical values of t_{rise} = 17 ms and t_{fall}=32 ms for the KDS monitor.

Contrast measurements under illumination according to the standards require specific lighting conditions. The Westar system is equipped with fixtures allowing for an easy mounting of light sources in the prescribed geometrical conditions. We have purchased three different light sources to satisfy different requirements. Ambient contrast measurements according to VESA 308-1,-2 require a large hemisphere to be mounted on the platform. By means of two properly baffled tungsten-halogen lamps, the hemisphere provides diffuse illumination of the sample. The current control of the power supply of the bulb allows to tune the color temperature to the CCT value for illuminant A (T=2856K), and the shutters provide for the control of illuminance to the prescribed 500 lux value without any modification of the color temperature. The NIST traceable white diffusion standard gives us the capability of determining the total reflectance of the DUT.

The military standard MIL-85762 defines daylight legibility and readability for contrast under sunlight illumination. This standard requires two light sources with color temperatures in the range 3000-6500 K. The standard requires both diffuse and specular reflected luminance to be measured.

For diffuse reflected luminance measurement, the source is adjusted to produce 10,000 fL, and the illuminated sample is measured with a photometer at 30°. The data are normalized to a diffusion standard. The specular reflected luminance measurement requires a light source producing 2000fL at the sample. The source and the detector must be positioned at 30° and on the opposite sides of the normal to the display. Data are normalized to a calibrated mirror. On the Westar platform fixtures are available to mount light sources at the 30° angle. At the same time, it is possible to vary the distance of the lamp from the DUT, in order to modify illuminance to the desired value. We performed test measurements of contrast under these illumination conditions using a newspaper, which is an example of a good quality reflective display. The Wall Street Journal white paper has a total reflectivity of 57.7% under 500 lux ambient light and a contrast of 2.7. Contrast under sunlight illumination of 10000 fL (the intense illumination according to MIL-85762) is reduced to 1.4 and specular reflection is negligible.

The described instrumentation is capable of a wide range of photometric measurements and can also perform them automatically, with considerable time savings for the operator. At the same time, the system is very flexible, and allows new fixtures and new configurations to be added easily, thanks to threaded holes on every surface and a wide range of motion. New automated measurements can be programmed and added to the existing ones, and when a more sophisticated approach is required, a new instrument (e.g. Radiant Imaging Camera) can be added to the list of supported detectors.

5. OBTAIN DATA ON COMMERCIAL OFF-THE-SHELF (COTS) DISPLAYS

As a part of the Cooperative Agreement, we have started to gather information on commercial display products for the construction of an electronic database. The construction of the database is the subject of the follow-up program.

For each of the companies that have been included in the database, we obtained the following information:

- display name or model #
- display type (ex: LCD, LCoS, etc.)
- display resolution (ex: XGA, SXGA, etc.)
- display technology (ex: CRTs, HMDs, etc.)
- display weight
- display size
- display specifications
- contact and company information

The majority of the data collected was through secondary research, which is being conducted through an on-line Internet search. However, some of the information has been a result of conversations with sales representatives who are listed as contact persons for specific display products. A portion of the data has also been collected through review of business technology journals, such as The Journal of Electronic Defense (JED) and Real Time Graphics.

6. FINANCIAL STATUS

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Commitments (as of 8/30/02):	$ 203,489.70
Balance (as of 8/30/02):	$ 6,526.74